Electric Ship Research and Development Consortium

The University of Texas at Austin

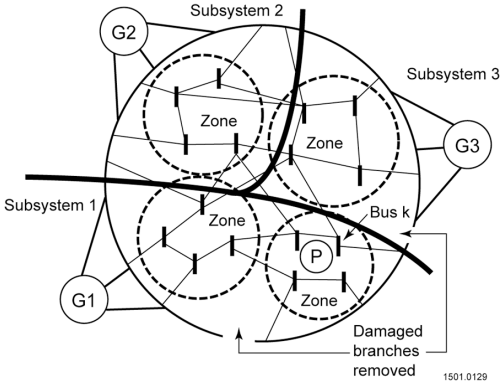
Dr. Joe Beno and Dr. Bob Hebner

University of Texas

Power Systems for Electric Ships

Consortium Effort

- Florida State University
- Mississippi State University
- University of South Carolina
- University of Texas



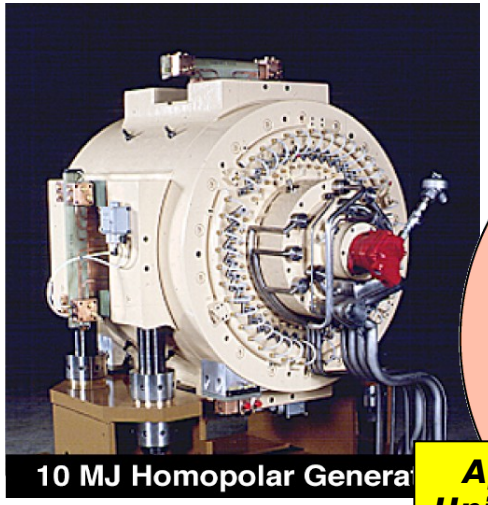
Reconfiguration Analysis for Three Generator System

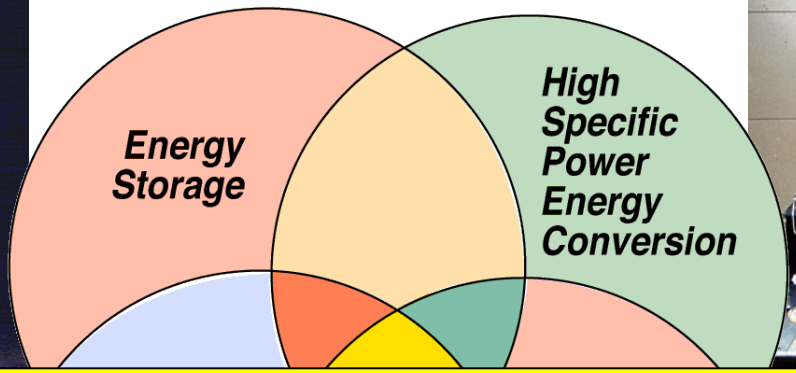
University of Texas Technology Development Areas

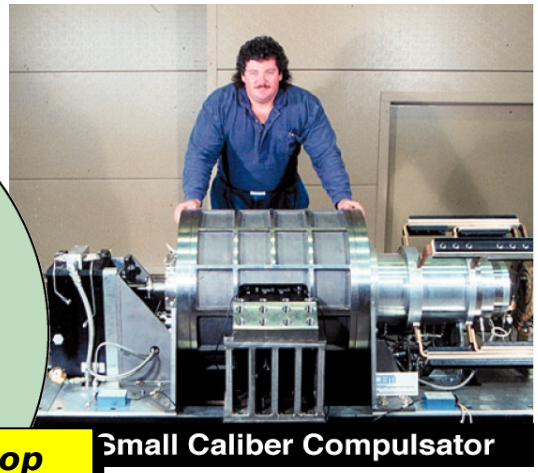
- Power System Dynamic Reconfigurability, Controls, and Thermal Management
- High Power Density Power Systems

CENTER FOR ELECTROMECHANICS

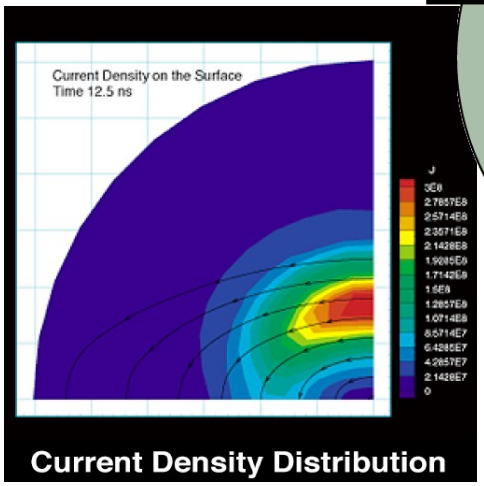
Core Research Areas Facilitate Interdisciplinary Development Progra


10 MJ Homopolar Genera



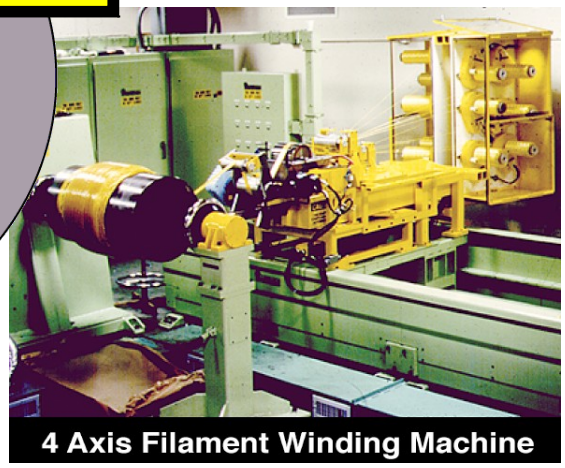

Small Caliber Compulsator

Application oriented R&D projects develop Unique capabilities in our core research areas

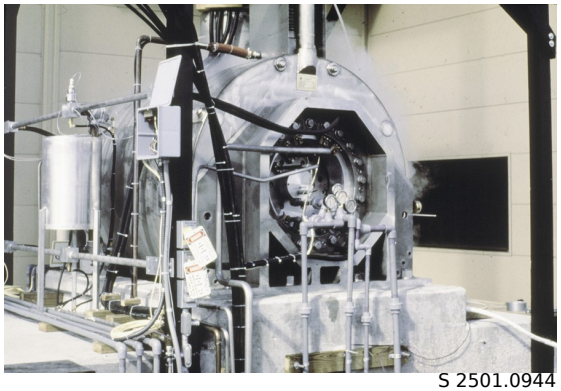


Current Density Distribution

Full time professional staff
$12-18M R&D per year

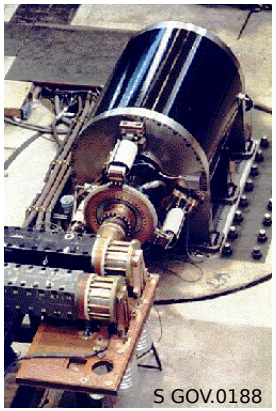

4 Axis Filament Winding Machine

CEM Flywheel Energy Storage Demonstrations



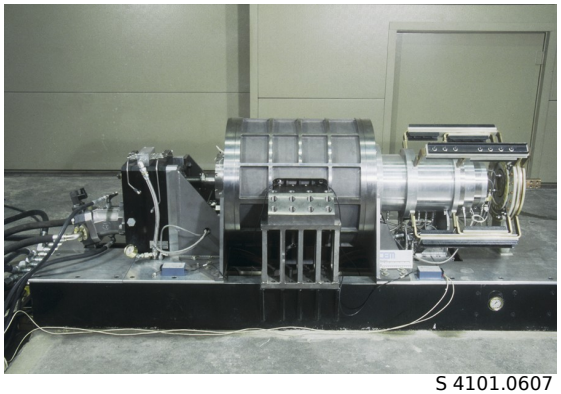
S 2501.0944

Super Conducting Homopolar Generator
13 kW, 0.9 kW-h
(1986)



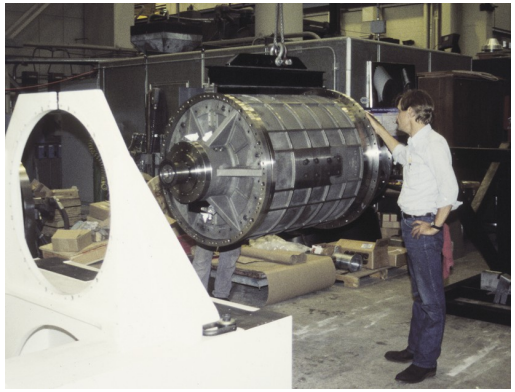
S GOV.0188

Iron Core Compulsator
800 MW, 10.5 kW-h
(1987)



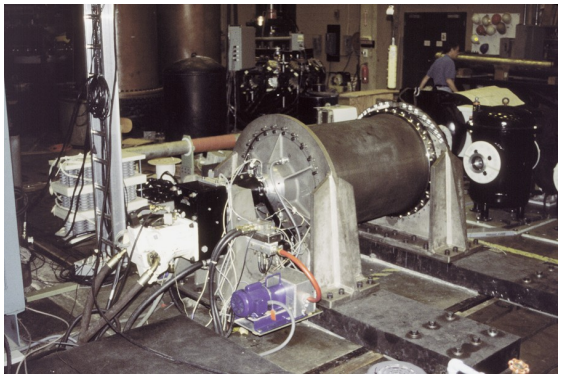
S 4101.0607

Composite Rotor Compulsator
664 MW, 2.5 kW-h
(1991)



S 3010.1993

Composite Rotor Compulsator
2.4 GW, 11 kW-h
(1995)



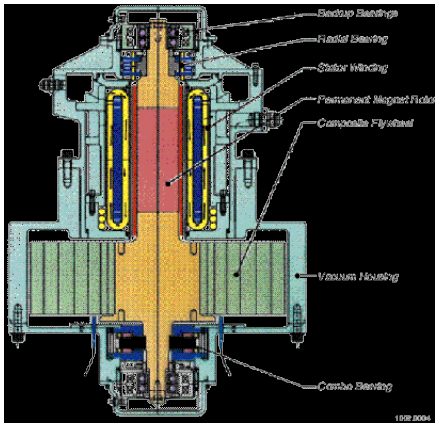
S 3910.1748

Composite Rotor Compulsato
3 GW, 6.4 kW-h
(1997)

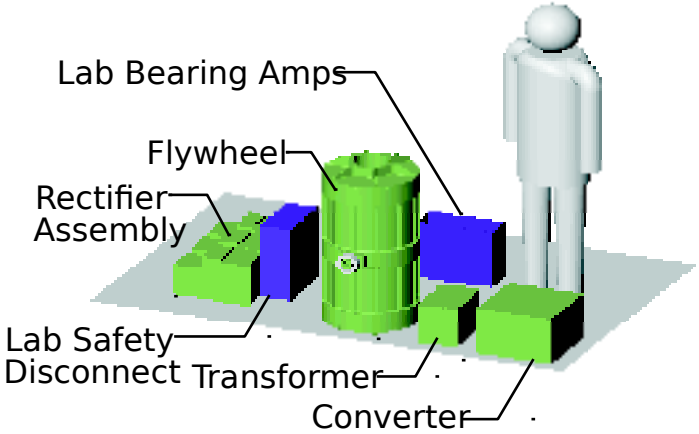
1002.1018

Mag. Bearing, Flywheel System
150 kW, 2 kW-h
(1999)

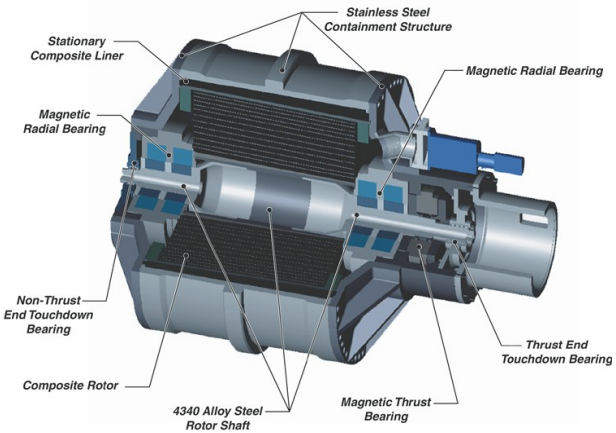
CEM Flywheel Systems with Magnetic Bearings



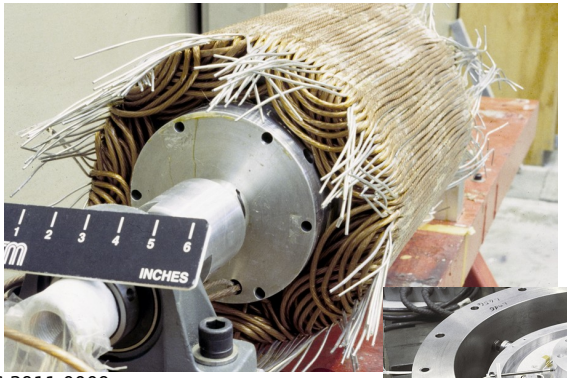
Transit Bus Flywheel
250 kW (peak), 110 kW (cont.), 2 kW-h



Combat Hybrid Power Systems (CHPS) Flywheel
10 MW (peak), 350 kW (cont.), 7 kW-h



Advanced Locomotive Propulsion System Flywheel
3 MW (peak), 2 MW (cont.), 130 kW-h

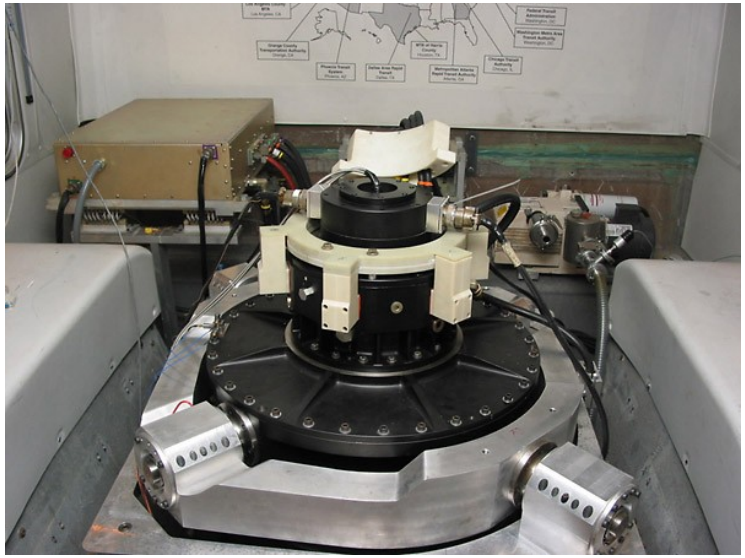


S 3911.0009

CHPS Component Verification

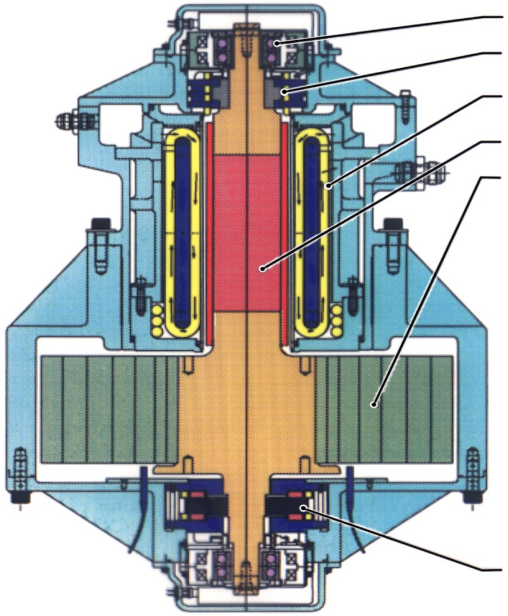
S 3911.0235

Transit Bus Flywheel Energy Storage System



Energy Storage: **2 kWhr stored, 1 kWhr delivered**
Power: **150 kW peak, 110 kW cont.,**
Between 30,000 and 40,000 RPM

Composite tip speed: **930 m/s at 40,00 rpm**
Application: **Power averaging for 15 ton**
Hybrid Electric Bus



Materials

- Aluminum
- Ceramic
- Permanent Magnet
- Windings
- Titanium
- Inconel
- Composite
- Stainless Steel
- Steel

CEM Flywheel Safety and Containment Programs

EV FW Safety and Containment Program

(DARPA & Industry, $8M, 96-02)

- **Phase I –** Flywheel failure modes
- **Phase II –** Containment loads and design
- **Phase III –** Containment demonstrations
- **Phase IV –** Flywheel fatigue

Transit Bus FW Safety Program

(Houston Metro, DARPA, Industry, $1M, 98-02) – Failure initiators, gimbals/platform integration, containment testing

Space Station FW Program

(NASA, $500K) – Fatigue testing, space qualification

Rotor Safe-Life Program

($200K+, NASA, DARPA, FTA, FRA) – Design allowables at end of

Defense In Depth Philosophy

First Line of Defense: Flywheel Design

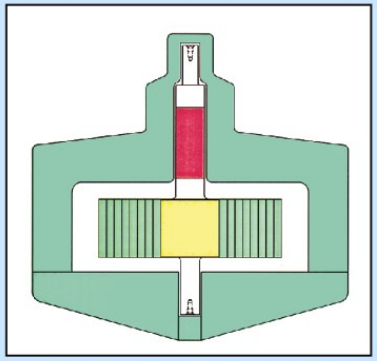
- Careful flywheel design minimizes accident risk
  - — appropriate design margins
  - — spin test to overspeed
  - — life cycle tests
  - — mechanical fuse
- Released burst energy is design and material dependent

Second Line of Defense: Flywheel Monitoring

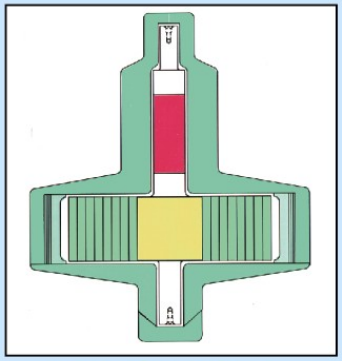
- Sensors detect abnormal conditions and safely shut down system

Sensed Parameter	Sensor Type
• Rotor Speed Vibration	Inductive proximity probe
• Flywheel Temperature	Infrared probe
• Vacuum Level	Vacuum gauge

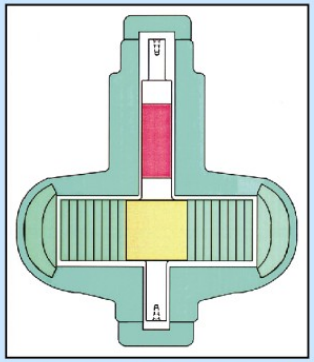
Third Line of Defense: Barrier Safety Systems to Mitigate Effects of Flywheel Failure



Rigid Pressure Vessel



Rotatable Liner



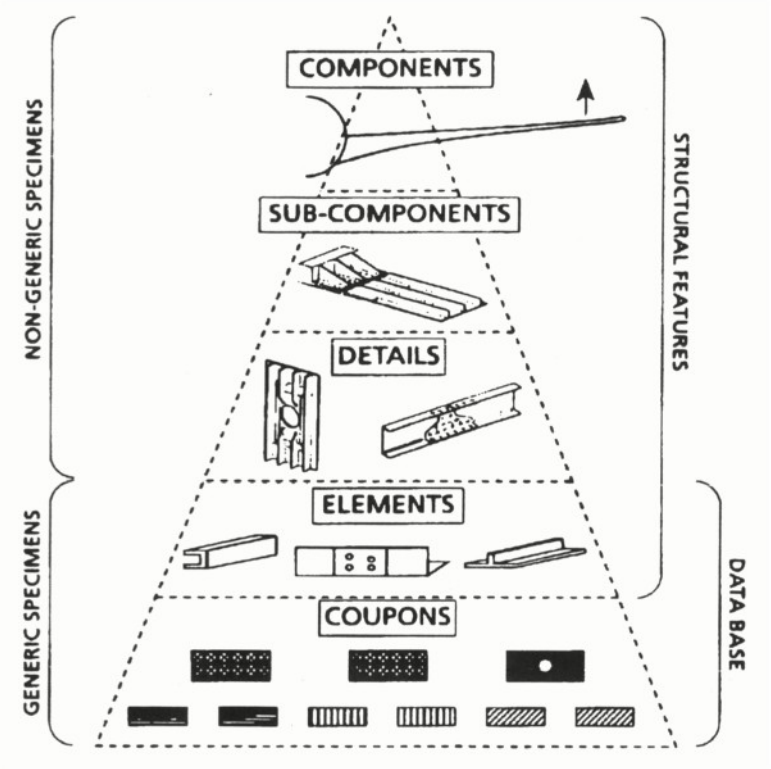
Energy Absorbing Liner

Other Approaches

- Combination of these design concepts
- No Containment

Military Handbook 17 Building Block Approach

- Generate material basis values and preliminary design allowables
- Based on structure design and analysis, select critical features for test verification
- Determine strength critical failure mode for selected design feature
- Determine tests that will produce critical failure modes
- Conduct series of tests on test specimens, compare to analytical models and adjust as necessary
- Design and conduct increasingly more complicated tests for various loading scenarios
- Conduct full-scale component static and fatigue testing



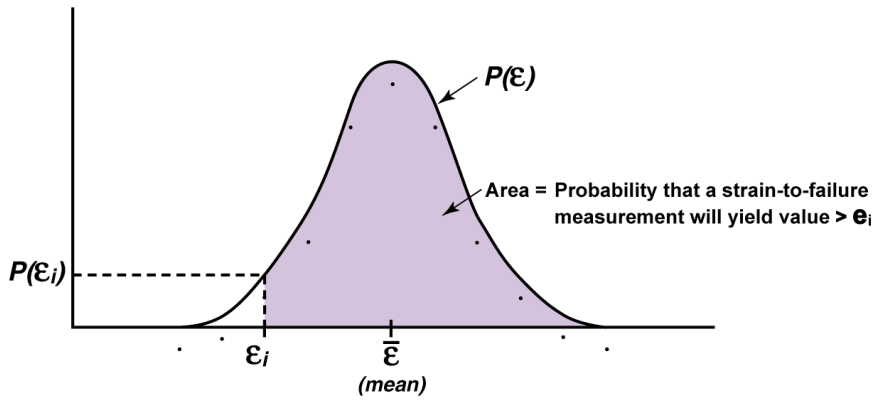
MIL-HDBK<17-1E

Probabilistic Design Approach For Advanced Composite Rotors

Requires:

Identification of composite material property of interest

- **Measurable**
- **Obeys statistical distribution function (currently using Student's "t", may switch to Weibull)**



Major Finding: Hoop strain to failure is good basis for flywheel design.

Development of measurement process

- **Relevant to design process**
- **Has identifiable uncertainty interval, δx**
- **δx much smaller than standard deviation of property**
- **Desirable if δx very small so statistical treatment of measurement process can be avoided (small penalty to simply use pessimistic**

Example: Safety Approach for International Space station (ISS) Flywheel Design

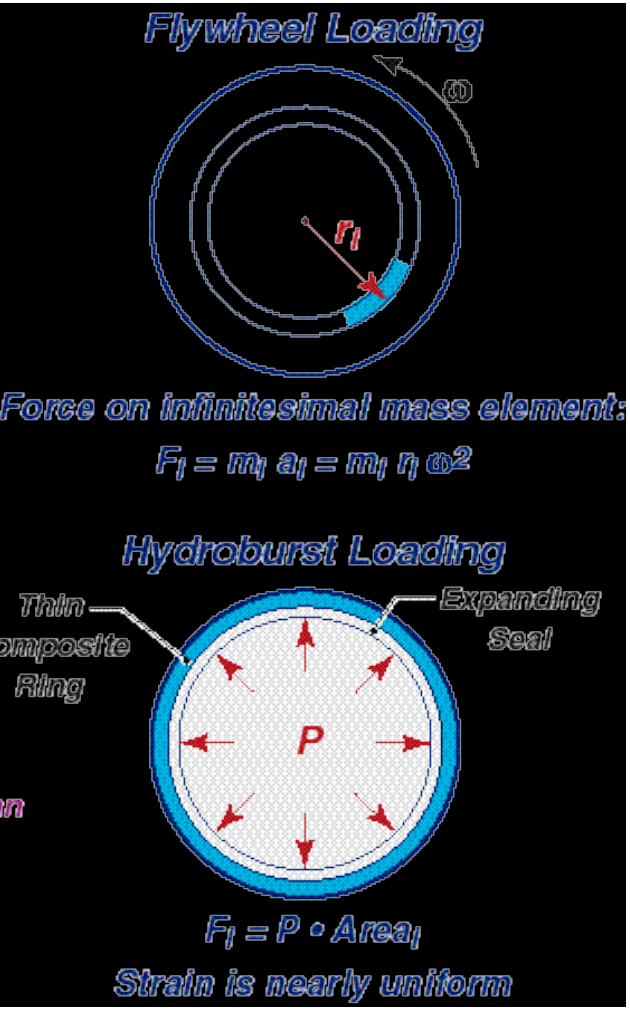
Approach: No containment; Probability of not having catastrophic failure > 0.999999

Comparisons

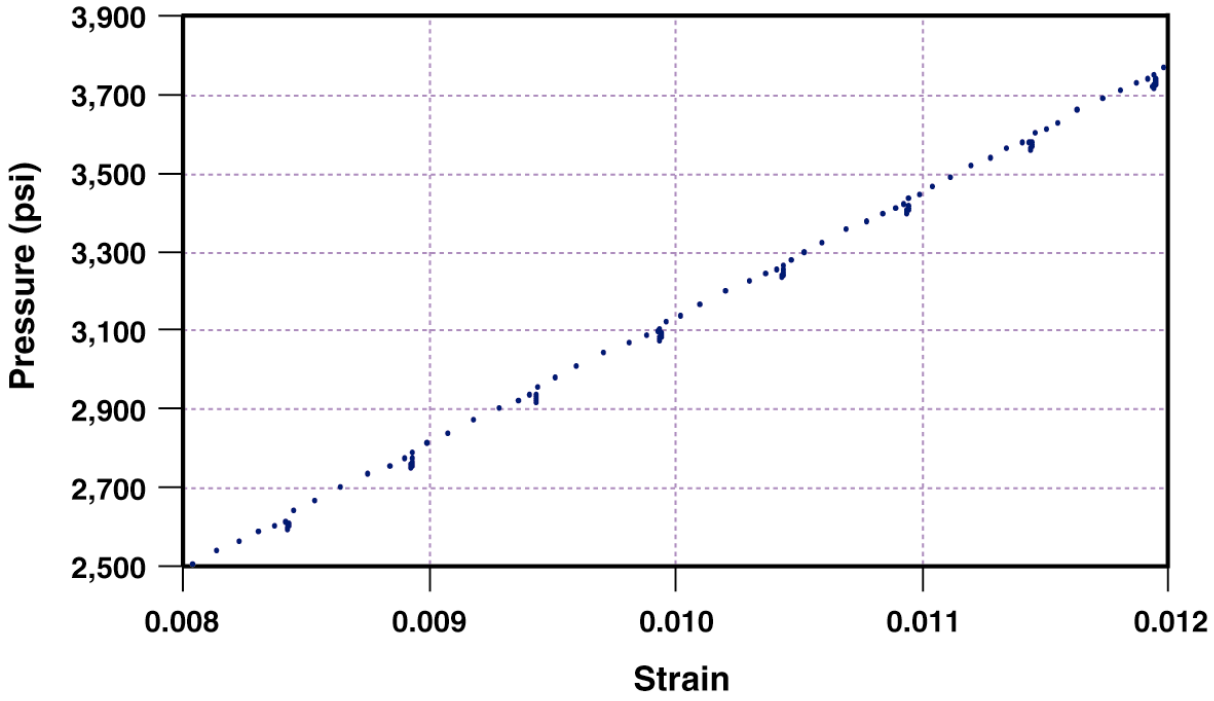
U.S. Army (1992) helicopter safelife components fatigue design	0.999999 (0.9_6)
Airbus aircraft (system reliability against catastrophic failures per flight year)	0.9_6
Airplane landing gear (system reliability against fatal accident per landing)	0.9_6
Boeing Helicopter (1991) rotorcraft component design	0.9_6
U.S. Army (1998) Light Experimental Helicopter Program	0.9_6
Oil rig platform (reliability against class III failure per platform year)	0.9_6
Automotive transmission components (typical over warranty life)	0.9_6
CEM transit bus flywheel, probability of not bursting	0.9_8

Measurement Process: Hydroburst Test

- For thin hydroburst ring, loading approximates flywheel composite loading
- Hydroburst ring must be thick enough that lamina configuration represents flywheel (CEM uses ~0.1 in.) and tall enough to reduce end effects (CEM uses ~0.5 in.)
- Hydroburst Instrumentation
  - Pressure:
    - Perfect pressure gauge reading is greater than pressure applied to hydroburst ring
  - Strain gauges:
    - Perfect strain gauge reading is less than or equal to strain-to-failure.

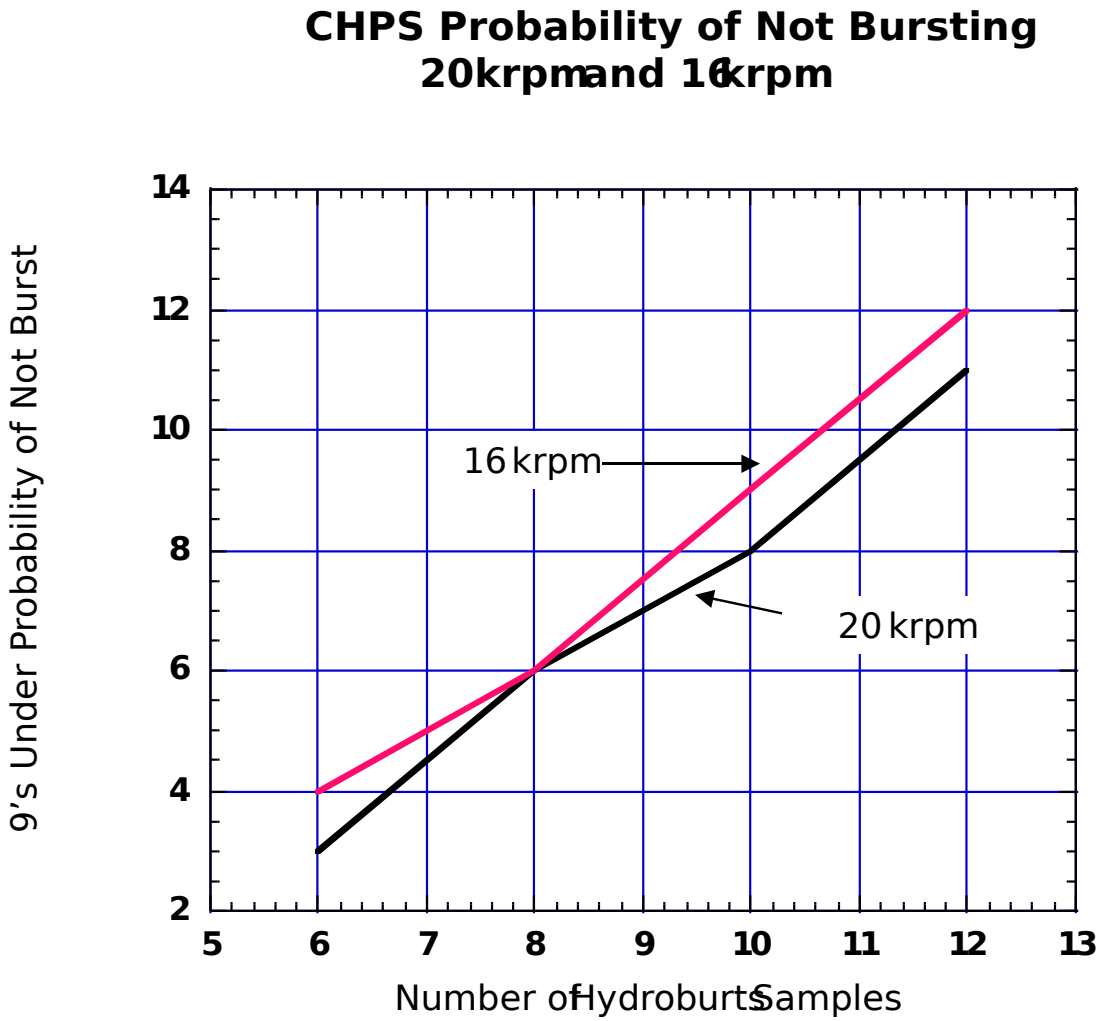


Hydroburst Data—Pressure vs. Strain



Friction in hydroburst apparatus degrades absolute pressure information, but the highly linear curve is typical and provides good tangent modulus estimate

CHPS Flywheel Safety



Overview of Test Devices, Inc. On-line Rotor Health Monitor

US Patent 6,098,022

Past experience:

- **Industrial applications for the last 3 years**
- **Used successfully for spin pit testing on jet engine disks and, more recently, flywheel assemblies**
- **Monitors mass balance state, detects unbalance change real-time**

Can use magnetic bearing signal inputs, no additional sensors required

Sensitive to minor structural changes (cracks, loose bolts, fiber sling, others)

Flywheel Fatigue Tests

Two flywheels were fatigue tested under this program

For these tests:

- **Full scale(diameter) with reduced length**
- **flywheels (3” vs 5.25”), reduced cycle period for 50% DOD**

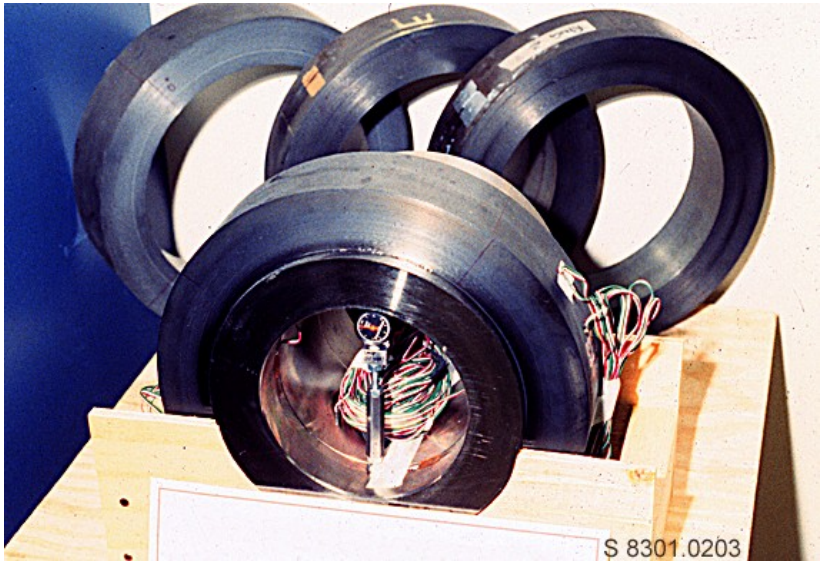
First flywheel fatigue test, tested to 20K cycles

- **After inspection, testing resumed at 36krpm/27krpm to 20,000 cycles without problems**
- **Slight fiber sling experienced**
- **Investigation concluded fiber sling was due to raw material flaw: localized section of resin lean material**

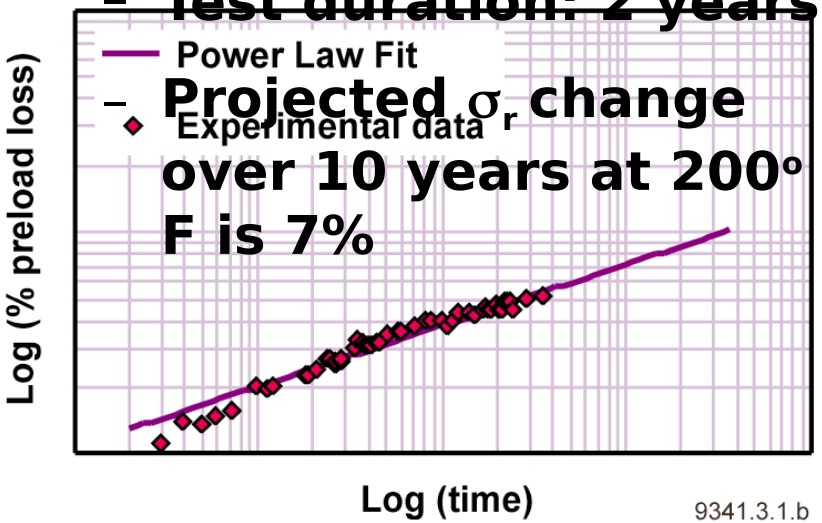
Second flywheel fatigue test, tested to 112,000 cycles – Terminated due to funding

Other Supporting Tests

- **Hydroburst coupon tests**
  - **UTS up to 200° F**
  - **Fatigue up to 200° F to 400,000 cycles (NASA FESS)**



- **Creep/stress relaxation tests**
  - **Monitor steel rings' dimensional change vs time and temperature**
  - **Infer change in preload, σ_r**
  - **Test duration: 2 years**
  - **Projected σ_r change over 10 years at 200° F is 7%**



Standardization Activities: Flywheel Rotor Safe Life Working Group

Government Sponsors:

Kerry L. McLallin, NASA Glenn Research Center

Dr. Jerry Fausz, AFRL - Phillips Lab

Center for Electromechanics
Penn State University
Lockheed Martin
Honeywell
Flywheel Energy Systems/Canada
National Research Council/Canada
Toray Composite America
Beacon Power
Boeing Seattle
Barbour Stockwell
Oak Ridge National Lab
Lincoln Composites
Test Devices, Inc

Objective

- Develop an industry consensus standard for the certification of flywheel rotors for aerospace applications
- Assure that flywheel rotors developed for government missions can meet safety and life requirements

Status

- Final draft will be completed in 6 months
- Am. Institute of Aeronautics and Astronautics (AIAA) has agreed to accept the draft standard for review
- AIAA will assemble a review panel (industry, government,

Conclusion

Flywheels Are A Viable Energy Storage Technology for the Electric Warship.

- **Integration technology, safety technology, end-of-life design technology require continued maturation.**

- **Development time line compatible with Electric Warship needs.**